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# REVIEW ARTICLE

## BALLISTOCARDIOGRAPHY: A CLINICAL REVIEW*

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THE PRESENT STATUS of ballistocardiography is highly controversial. Literature on the subject is rapidly growing and contains confusing and sometimes diametrically opposed opinions. There are those who make extravagant claims and present conclusions highly questionable. And there are many conservative investigators who feel that the ballistocardiograph is still a research tool and as such should not be applied clinically. Despite this conflict the ballistocardiograph is being used clinically by an ever-increasing number of physicians and it now appears to be assuming a position in the cardiac assessment of the patient.

A ballistocardiograph is an instrument that records the motions of the body imparted to it by the heart beat. One has only to stand erect on a spring weighing machine to be aware that the body moves rhythmically synchronous with the pulse. If this small motion were magnified many thousand times and recorded, the result would be a ballistocardiogram. This fascinating observation was made by Gordon as far back as 1877.[1] He was the first to record the ballistic forces of the body. By placing a subject on a bed suspended by ropes from the ceiling he obtained a record of its motion synchronous with the heart beat. Subsequently, further sporadic work was done by a number of investigators but during the years no great contribution was made. In 1939 Isaac Starr and his associates published their investigations,[2] and thus modern ballistocardiography was born. With this work a new era of investigation in this field was begun. In 1949 Dock introduced methods of recording the ballistocardiogram directly from the body.[3] These direct, more simplified techniques allowed a greater scope of investigation and clinical application, and established ballistocardiography as an office procedure.

### TECHNIQUES AND PHYSICAL PRINCIPLE

The physical principle of the ballistocardiograph is Newton's third law of motion, namely that for every action there is an equal and opposite reaction. Accordingly, if the body exerts a certain force on a specific amount of blood, this blood in turn will exert an equal but opposite force on the body.

Most of the ballistocardiographic methods in use today record the motion of the body in the longitudinal axis. It is, however, well recognized that important vectors associated with blood flow may be transmitted in other directions, particularly in cardiac disease. To this end some work has been reported on the lateral and dorsoventral ballistocardiograms.[4-6]

There are at present three different types of ballistocardiographs in common use: (1) the high frequency undamped table of Starr;[2] (2) the low frequency critically damped table of Nickerson,[7] and (3) the direct body pick up designed by Dock.[3] Despite differences in construction and physical considerations the ballistocardiograms they yield are roughly quite similar. The direct body pickups, however, are much less expensive and simpler in their construction and application. They are of two general types, the photoelectric and electromagnetic, each utilizing a different physical principle.

Other ballistocardiographs have been developed, but the types mentioned above still have the greatest clinical application.

### DISCUSSION OF TECHNIQUES

Theoretically if one could isolate and record the pure forces generated solely within the cardiovascular system, then indeed a true measure of cardiac power would be realized. This determination, however, is extremely complex and difficult and present-day techniques of ballistocardiography are certainly deficient in this regard.

The human body can be considered to be composed of springs and masses. The heart and circulatory system rest on a rigid skeleton and interposed between them are various tissues having elastic properties. Because of its construction the body like other physical systems has a specific frequency response pattern when it is set in motion by an applied force. It is highly damped but not critically damped since after being displaced it oscillates back and forth several times before coming to rest.

Since the forces generated by the heart are transmitted through the body tissues and skeleton before reaching the recording system, it is apparent that they may be subject to distortion and modification. The body make-up therefore prohibits the recording of pure cardiac forces. As Starr so aptly stated,[8] "It is sobering for all ballistocardiographers to remember that we can never hope to record with absolute accuracy forces generated in the centre of the body by apparatus placed outside it, because the body tissues are not a perfect medium for the transmission of the forces."

Moreover, it is also well established that all the instruments in use today suffer from their own peculiar failings and therefore contribute to the confusion of modern ballistocardiography. Analysis of the current methods has revealed distortions which cast considerable doubt on the true interpretation of the ballistic waves.[9, 10]

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When modern ballistocardiography was first introduced, it was felt that the records could be interpreted quantitatively as a function of cardiac output. This concept, however, has since been questioned and at present it is generally accepted that ballistic interpretation can be approached only from an empirical qualitative viewpoint.

From the above discussion it is evident that the question of ballistocardiography is replete with difficulties. Summarizing, there are two major obstacles which face the ballistocardiographer. The human body is an imperfect medium for the transmission of cardiovascular forces, and the instruments in use today are all deficient to the point of distorting the ballistic waves. The distortions are mainly due to oscillations introduced by the techniques, either by their coupling effect to the body or by their own natural frequency. These oscillations apparently have no cardiovascular meaning and their frequencies fall into the ballistic range of the body, causing extraneous distortions. And finally, the body, because it lies on a rigid surface as in the direct body pickups or on a constrained platform as in the table techniques, oscillates on its own tissues and this introduces further sources of error.

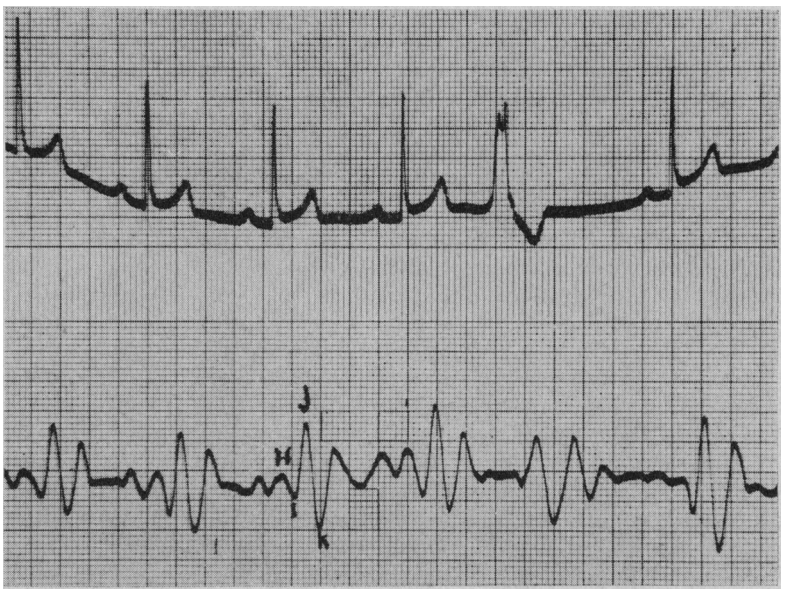


Fig. 1.—Normal trace from a young girl with myasthenia gravis. Note ventricular extrasystole.

Theoretically it should be possible to obviate the major difficulty by freeing the body of all restoring and damping forces. If the body could be made to "float on air", it would respond only to the forces from within that set it in motion and not oscillate on its own tissues. In this way a relatively accurate representation of the cardiovascular forces would be effected. The interest and stimulus at present is indeed directed to this end, and accordingly Burger[11] has constructed a very low frequency table while Talbot and his group[12] have designed an aperiodic ballistocardiograph. An interesting innovation that awaits clinical study is Schwarzchild's aperiodic system that utilizes the conventional coil and magnetic transducer.[13]

The evaluation of these newer techniques is still not complete, and certainly not enough material has been collected for proper clinical assessment. It appears, however, that from a pure physical and mathematical approach these instruments may more accurately represent cardiovascular forces. If this be so, then the physiological interpretation of the ballistic components should be facilitated and clarified. It remains to be seen, however, whether they yield any more clinical information than the earlier instruments.

Any discussion therefore of the clinical aspect of ballistocardiography must be done with some reservation, always remembering that we are dealing with a physically imperfect recorder. There are, however, certain clinical observations which are highly significant and indeed appear to justify the position of the clinical ballistocardiographer.

## THE NORMAL BALLISTOCARDIOGRAM

Coincident with the heart beat is a consistent reproducible pattern in normal people (Fig. 1). The waves comprising this pattern have been designated by Starr as the H, I, J, K, L, M and N waves.[2] The dominant waves are the H, I, J, K, and L, and their collective shape resembles the letter W. All the techniques are so constructed that in the longitudinal direction a headward motion of the body records as an upward wave deflection and a footward motion a downward wave deflection. The H, I, J, K waves are usually referred to as the systolic waves and the L, M, N as the diastolic waves.

In normal subjects during quiet breathing there is some degree of respiratory variation; the I-J amplitude is greater during inspiration than during expiration. The range of variation may be wide but in most cases is a modest one.

The regularity and consistency of the beat pattern is a prominent and important feature of the normal ballistocardiogram. The occasional abnormal complex is of no significance and in all probability is an artefact. A slight movement of the body or a heavy vibration in the building, as from a passing vehicle, may introduce extraneous vibrations. The rule of interpretation is that abnormality in form must be repeated before a record is labelled abnormal.

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The amplitude of the waves, particularly the dominant I-J stroke, should normally be within a certain range.

Probably the most desirable method of establishing the range for a particular instrument is to test it against a series of normal young people. Once this has been determined, inspection alone must suffice to classify the amplitude as normal or abnormal. Most investigators interpret the ballistocardiogram on a qualitative empirical basis, as quantitative determinations are considered inaccurate.

The diastolic waves should in the normal record be of smaller size than the systolic components. If they are excessively large or they dominate the record, they suggest abnormality.

Summarizing, a normal trace should consist of the following points. The systolic waves should dominate and should be shaped like the letter W. The diastolic components should be smaller. There should be no marked notching or slurring of the individual components. The pattern should be consistent and reproducible. There is a normal respiratory variation in amplitude, and the amplitude of the waves should be within a certain empirically established range.

From the above discussion of the normal ballistocardiogram it is apparent that abnormal records might differ in amplitude or in form or both.

Many different studies have been completed in different laboratories using the various techniques and there appears to be universal agreement that under the age of 50 apparently normal individuals yield normal ballistocardiograms with little exception, but after the age of 50 the incidence of abnormal records amongst apparently normal people is relatively high.[14-17]

The *genesis of the ballistic waves* is still highly controversial and in many instances conjectural. Starr in his fascinating cadaver experiments has shown that a decrease in the velocity of ventricular ejection may affect the shape and size of the individual systolic components.[8, 18] The diastolic waves are even more baffling, some investigators suggesting that they are merely after vibrations and others imputing specific relationship to them, such as the blood returning to the ventricles.

As has been mentioned, the I-J stroke normally increases during inspiration and appears decreased during expiration. Starr and Friedland[20] have beautifully demonstrated that this ballistic respiratory variation is dependent on the changes in intrathoracic pressure with its associated volume changes and not in the changes of cardiac position. With this reversal of intrathoracic pressure they demonstrated a similar reversal of the ballistocardiographic respiratory variation.

Another factor that is believed to influence the respiratory variation is the pulmonary reservoir.[19, 21] This vascular pool in the lungs responds to intrathoracic pressure changes so that it is augmented during inspiration and diminished during expiration.

In some cases a marked respiratory variation that affects a minimum of complexes should not necessarily be considered abnormal. As Dock pointed out, flabby abdominal musculature, loss of elasticity of the great vessels or emphysema may be the main factor in some of these cases.[19] Moreover, Starr suggests that any normal person can cause an abnormal respiratory variation merely by hyperventilation and apprehension.[22]

Respiratory variation therefore, though it may indicate cardiovascular disease, may be caused by extracardiac factors, particularly if a minority of complexes are involved. This fact should be borne in mind before labelling this phenomenon as abnormal.

## CARDIAC OUTPUT AND THE BALLISTOCARDIOGRAM

In his more recent work Starr[18, 23] has shown that the amplitude of the ballistocardiogram is very closely related to the maximum velocity of ejection and this in turn is a reflection of the force of the heart.

By simulating cardiac systole in cadavers he has experimentally demonstrated that the amplitude of the systolic waves of the ballistocardiogram is dependent on the velocity of ejection and cardiac force and not on the volume ejected. By changing the velocity while maintaining a constant volume the amplitude was accordingly changed.

His fascinating work demonstrated that when maximum velocity was obtained early in systole the resultant ballistocardiogram was perfectly normal. However, when simulated systole was weak and maximum velocity was delayed into late systole, the ballistic form became grossly abnormal.

Clinically it appears that there is some rough relationship between the amplitude of the ballistic waves and the stroke volume, for in those conditions known to increase the stroke volume, such as aortic insufficiency and hyperthyroidism, augmented ballistic waves are usually seen.

With the above considerations in mind, one may summarize the problem by stating that the amplitude of the ballistic waves is decided by cardiac output, cardiac force or power, the velocity of ejection and possibly other unknown factors. Each factor or their combinations may conceivably affect the amplitude.

## THE ABNORMAL BALLISTOCARDIOGRAM

Most ballistocardiographers interpret the records qualitatively. Brown and his associates[24] have classified abnormal records into four major groups. Their classification is widely accepted by most observers and with some modification by others.

GRADE 1

The regularity and definitiveness of the ballistic waves is preserved. The expiratory I-J complexes are decreased in amplitude to less than 50% of those of inspiration, which are normal.

GRADE 2

This grade is a more extreme form of the above. Here more than one-half the expiratory complexes are abnormally small. Some of these small complexes may be of abnormal form.

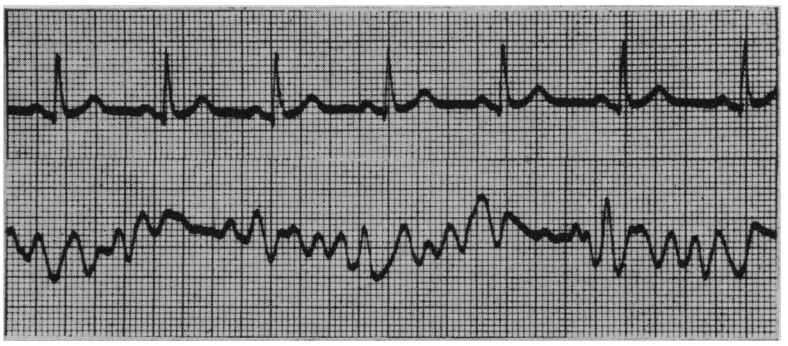

Fig. 2.—Grade 4 pattern from a man, 45 years of age, with severe angina pectoris.

GRADE 3

Abnormalities in form of varying degree are present in both inspiration and expiration, but many complexes are still identifiable. Most of the complexes are low in amplitude.

GRADE 4

The waves are all unidentifiable and of low amplitude.

As mentioned previously, there are some who doubt whether abnormal respiratory variations affecting some complexes are due to cardiovascular disease. Grade 1, therefore, of the above classification may be within the normal range for some persons. And, finally, any individual wave can be diminished or "cut off". This is particularly seen with the I wave and J wave.

No abnormality is specific, for many diseases may cause the same changes in the ballistocardiogram.

## AGE AND THE BALLISTOCARDIOGRAM

Studies already referred to of presumably normal people have shown that there is a high incidence of abnormal records beyond the age of 40 and 50. Starr followed up many of these patients for 10 years and found that a high percentage of them developed heart disease.[25] He concludes that a ballistocardiogram abnormal in form or of unusually low amplitude suggests a serious prognosis. However, there are many subjects with abnormal records who remain asymptomatic, and moreover Starr has reported subjects with normal records developing myocardial infarction.[22]

It is well documented that the incidence of coronary vessel disease increases with age,[26] and it is interesting to note the parallel between this observation and the increased incidence of abnormal ballistocardiograms with senescence. Possibly then, some of these abnormal records may be due to latent or subclinical coronary vessel disease. However, before this conclusion can be reached, more follow-up material must be assessed. Certainly at this point not enough data have accumulated to warrant this important conclusion. Moreover, as has been repeatedly pointed out, extracardiac factors can produce abnormal ballistocardiograms particularly of the Grade 1 type. Therefore to label an abnormal record in a person obviously healthy and asymptomatic as one of poor prognosis is at present unjustified. The possible relationship to future heart disease should always be kept in mind and a more careful observation of the patient be undertaken.

Furthermore, both Dock and Starr[19, 8] suggest that with advancing age the heart like other muscles of the body might conceivably undergo an aging process exclusive of coronary artery disease, and this might lead to diminution of cardiac strength. This seems like an attractive concept and might explain some of the abnormal records beyond the age of 50.

## THE BALLISTOCARDIOGRAM IN CORONARY VESSEL DISEASE

Since its introduction the ballistocardiogram has been used with great interest in the evaluation of patients with coronary heart disease. Starr was the first to show the relationship between this condition and an abnormal ballistocardiogram (Fig. 2).

Scarborough and associates[27] examined 191 cases of angina and found that 75.4% had abnormal records. However, there was an increasing incidence of abnormalities in the older age groups. Only 54% below the age of 50 had abnormal records, whereas above 50 the incidence was 84%. Dock and his group[16] found an abnormal resting ballistocardiogram in 92% of 152 cases of angina. Furthermore, a general correlation appeared to exist between the severity of the angina and the degree of abnormality.

Moser and his group[28] studied the ballistocardiogram in 100 cases after myocardial infarction. They found 81 abnormal and 19 normal records. The electrocardiogram was abnormal in 74 of the abnormal group and in 17 of the normal group.

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Many other studies have been done and have supported the general findings reported above. There appears to be a good correlation between coronary artery disease and an abnormal ballistic record. This abnormality appears more frequently in the older age groups.

The types of abnormalities found in these different series are very diverse and non-specific. Abnormalities of the individual waves can occur, such as short or absent I waves, or any of Brown's four grades can exist. Accordingly it might follow that the degree of abnormality might be an index to prognosis after angina pectoris or myocardial infarction. Indeed, Dock[19] has reviewed 100 cases following acute infarction and has shown that there is a higher degree of morbidity and mortality in the cases with the more abnormal ballistocardiogram.

As yet, enough data have not been accumulated to justify prognosis on the basis of the ballistocardiogram, but it appears that a normal or minimally abnormal record following an acute episode may bespeak a more favourable future. As mentioned previously, myocardial infarction has been noted in persons with normal ballistic records and so the whole problem of prognosis awaits further documentation.

### THE EFFECT OF SMOKING ON THE BALLISTOCARDIOGRAM

The effect of nicotine on the ballistocardiogram has created much speculation and interest. It has been observed that a high percentage of patients with coronary vessel disease develop a deterioration in their ballistocardiogram after smoking a cigarette.[29]

The abnormalities found in a positive cigarette test are again non-specific and any change can occur. Large diastolic waves are commonly seen. The cause of the positive cigarette test is as yet not perfectly understood. However, several concepts have been proposed. Coronary and generalized arteriolar vasoconstriction and direct myocardial effect have all been suggested.

### THE BALLISTOCARDIOGRAM IN CONGENITAL AND ACQUIRED HEART DISEASE

Of all the conditions in the congenital heart group the one most often associated with the ballistocardiogram is coarctation of the aorta. Many observers[30-32] have confirmed the finding first observed by Hamilton[33] that most cases of coarctation have a diminished or "cut off" K wave (Fig. 3).

A diminished K wave is not specific for coarctation of the aorta as it has been seen in Eisenmenger's complex, interatrial septal defect and patent ductus arteriosus.[22, 32]

No other congenital heart conditions give a consistent change on the ballistocardiogram, and the underlying cardiac damage will determine the changes that may occur.

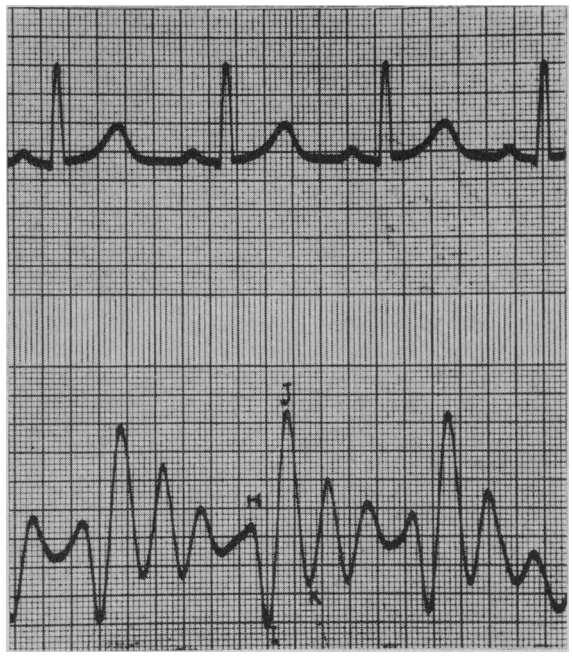

Fig. 3.—Cut off K wave in an established case of coarctation of aorta. Speed—50 mm.

Though patterns have been described for almost all types of rheumatic heart disease, they do not appear to be consistently found, as the ballistocardiogram may assume any of the changes previously described or may be normal, presumably depending on the amount of underlying cardiac damage.

It can be said, therefore, that in the diagnosis of congenital or rheumatic heart disease the ballistocardiogram is generally of no great help. In most cases of coarctation a consistent diminished K wave is present but this finding is not pathognomonic and has been reported in many other conditions, though not with the same frequency.

### SUMMARY

A general review of clinical ballistocardiography is given and the following considerations are presented.

1. The instruments in common use are all deficient and do not represent pure cardiac forces; the true physiological interpretation of the curves is therefore questionable.

2. In spite of its shortcomings ballistocardiography may be used as an adjunct in the diagnosis and assessment of cardiovascular disease but must be viewed with reservation.

3. Apparently normal individuals below the age of 50 have normal curves and the incidence of abnormalities increases with age. An abnormal ballistocardiogram in an apparently healthy young man should be treated with caution, while a normal curve in the older groups should be viewed with optimism.

4. There are no specific patterns for any particular disease in both the acquired and the congenital heart group.

5. The ballistocardiogram has its greatest clinical value in the field of coronary artery disease, where it is suggested that the more normal the curve the better the prognosis.

6. The newer instruments may clarify the entire field of ballistocardiography.

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## TERMINATION OF PREGNANCY ON PSYCHIATRIC GROUNDS

Attention is drawn by Arkle (*Brit. M. J.*, 1: 558, 1957) to the frequency of requests by patients and practitioners for termination of pregnancy on psychiatric grounds. The historical background and the present legal position are outlined, and the results of pregnancy in a series of cases referred for consultation on account of the mental state of the patients are summarized.

The conclusion is drawn that termination of pregnancy on account of the mental state of a patient is rarely justified by the law of Britain, and the doubtful wisdom of extending the indications for abortion, as in certain foreign countries, is discussed.

# PUBLIC RELATIONS FORUM

*Conducted by* L. W. HOLMES
Assistant Secretary, C.M.A.

## A FEW REQUIREMENTS OF A FAMILY DOCTOR*

LOTTA DEMPSEY

LIKE ALWAYS, nobody approached me when they were asking hundreds of people what kind of doctor they wanted.

So I'm going to tell them—now that the Montreal convention of the College of General Practice has been listening to the results of a survey of different occupational groups on their preferences in medicos.

The only occupational group I know anything about is the one occupied with being women—women who have the responsibility, largely, for the health and happiness of a husband and children. Which means, of course (although this is not taken into account sufficiently), they have the responsibility for their own personal health, as the pivot of family welfare.

I want a doctor who sees me first as a human being, and later, as a living mechanism which may be missing on a couple of cylinders.

I want—and I think thousands of women want—a healer, mentor and medically sound individual who is one of those professional men in our society still fulfilling the important functions of the vital port-in-all-storms: that of the family doctor.

I am shocked by the numbers of women, often in what the medical surveyors called the middle class or the professional and executive class, who do not call confidently at the office of a trusted doctor every six months (or year at most) for a checkup.

I am upset every time I hear people discussing a brilliant intern and saying, "but of course he's going to specialize". My heart rejoices, as it did the other day, when I meet one with a fine scholarship-studded record who prefers to go into general practice.

I want a doctor who realizes, as one told me he did, recently, that many women who consult him for the first time have cleaned out all the bureau drawers and mended the family's clothes before making an appointment.

In other words, they fear the worst and are scared stiff.

And I want a doctor who is aware I am watching every expression in his eyes as he takes my history, and assessing every phrase he uses (often, completely erroneously); and that I am in the swirl of the emotional uncertainty I might feel if I were a prisoner at the bar—one possessed of an utterly illogical sense of guilt.

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